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EFFECT ON COMBINED CYCLE EFFICIENCY OF STACK GAS TEMPERATURE CONSTRAINTS TO AVOID ACID CORROSION

Joseph J. Nainiger
National Aeronautics and Space Administration
Lewis Research Center

July 1980

Prepared for
U.S. DEPARTMENT OF ENERGY
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NOTICE

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by

Joseph J. Nainiger
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

The effect on combined cycle performance of raising the stack gas temperatures to levels high enough to avoid corrosion when burning fuels containing sulfur is presented and discussed. The use of fuels containing sulfur requires that the cold-end heat exchanger surface and exhaust stack gas temperatures be kept above the sulfuric acid condensation temperatures. Sulfur in the fuel results in acid formation which then requires a higher stack inlet temperature compared to low-sulfur fuel. Raising the exhaust stack gas temperature, however, results in lower combined cycle efficiency compared to a combined cycle system burning a sulfur-free fuel. Dew points were estimated as a function of fuel sulfur content and gas turbine design parameters. An emperical correlation was used for these dew point calculations. The effect on combined cycle efficiency was determined for air-cooled and water-cooled gas turbine combined cycle systems. Combined cycle performance calculations were made assuming first a sulfur-free fuel and then a fuel with 0.8 percent sulfur by weight. This is the maximum sulfur content for a liquid fuel that can be used without sulfur dioxide emission control devices and still meet environmental requlations. The maximum difference between the combined cycle performance using sulfur-free fuel and using the 0.8 percent sulfur fuel was less than one percentage point in efficiency.

INTRODUCTION

The combined cycle performance gains obtained by using thermal barrier coatings (TBC's) in gas turbine blades was previously investigated (ref. 1). The increase in combined cycle efficiency when using TBC's was 1.4 percentage points for an air-cooled turbine and 2.3 percentage points for a water-cooled turbine. In addition to improving performance, another potential benefit of using TBC's is that the coating could serve as corrosion protection for the airfoils and allow the use of lower cost fuels. These performance calculations in reference 1, however, did not take into account the use of fuel oils containing sulfur and the corresponding efficiency losses described above. When these losses are included in the analysis, the combined cycle efficiency gain for using a TBC with a fuel containing sulfur compared to a sulfur-free fuel fired combined cycle without TBC is 0.6 to 1.0 percentage points for the air-cooled systems and 1.6 to 1.8 percentage points for the water-cooled systems. Therefore, TBC's may permit the use of the minimally-processed (and hence less expensive) fuels which contain sulfur in gas turbines with an increase in efficiency. Without a TBC, the use of a minimally-processed fuel could require a reduction in gas turbine inlet temperature to achieve acceptable corrosion life and, hence, a reduction in efficiency.

The study described in this report was done as part of the Critical Research and Advanced Technology Support Project (CRT), which is being performed by the NASA-Lewis Research Center for the Department of Energy (DOE), Office of Coal Utilization. The purpose of the project is to provide technical support to DOE to accelerate the development of utility size, advanced, open cycle gas turbine systems using coal-derived fuels.

CASES STUDIED

The combined cycle cases that were studied are shown in Table 1. Both air-cooled and water-cooled gas turbine combined cycle systems were considered. For the air-cooled cases, the performance for a 1205° C (2200° F) base case burning a sulfur-free fuel and not employing a TBC was calculated. The second case assumed the use of TBC while keeping the gas turbine airfoil metal substrate temperature and total cooling airflow rates the same as in the first case. The TBC allowed the turbine inlet temperature to be much higher (1370° C (2500° F)) than the base case and, thus, the combined cycle efficiency is greater for a sulfur-free fuel. In these two cases the stack temperature was constrained only by the ability to heat the feedwater of the steam bottom cycle. The third case considered the same 1370° C (2500° F) gas turbine with TBC, but used a fuel with 0.8 percent sulfur. In this case the heat recovered from the exhaust gas was constrained so that the stack temperature remained above the dew point to avoid condensation of sulfuric acid.

Similarly, for the water-cooled gas turbine combined cycle case, the combined cycle performance for a base case burning a sulfur-free fuel at a turbine inlet temperature of 1649° C (3000° F) without TBC was calculated. The effect of a TBC on combined cycle performance was calculated for the water-cooled case by assuming the same gas turbine blade metal substrate temperature and gas turbine inlet temperature (1649° C (3000° F)). The TBC resulted in a reduction in heat losses from the gas to the cooled airfoils and resulted in increased efficiency. Finally, the effect of burning the 0.8 percent sulfur fuel was also investigated for the water-cooled case as previously described for the air-cooled case.

As indicated in Table 1, the effect of a TBC on the combined cycle efficiency was evaluated differently in the water-cooled cases than in the air-cooled cases. In the air-cooled cases the turbine inlet temperature was increased while keeping the gas turbine cooling airflow rate the same as the base case without a TBC. For the air-cooled cases, this was found to yield higher efficiency gains than keeping the turbine inlet temperature constant and reducing the coolant airflow (ref. 1). For the water-cooled case, turbine inlet temperature was kept the same as the base case without TBC and cooling flow was reduced. The effect of using TBC to raise the turbine inlet temperature above 1649° C (3000° F) was not evaluated, since this would present severe NO_x emission problems (which have not been addressed herein). Furthermore, it is not known how well the TBC could withstand such harsh operating environments.

ANALYSIS PROCEDURE

The first step of the analysis was to calculate the dew points of sulfuric acid in gas turbine exhaust products as a function of fuel sulfur and excess air. The following reactions describe the formation of sulfuric acid in the combustion products of a gas turbine:

(1) $S + O_2 \rightarrow SO_2$

(2) $SO_2 + 1/2\ O_2 \rightarrow SO_3$

(3) $SO_3 + H_2O \rightarrow H_2SO_4$

Experimental data indicates that only one to six percent of the SO_2 is converted to SO_3 (refs. 2 and 3), which is significantly less than equilibrium at typical exhaust conditions. The actual conversion rate will depend on the amount of excess air available and on the possible presence of oxidation catalysts in the fuel. The boiler tubes can also act as a catalyst in this reaction (ref. 2).

Another problem in determining the acid dew point is that the sulfuric acid is formed in dilute solutions. There appears to be little success in determining the necessary vapor pressure data for these solutions using a thermodynamic analysis (ref. 4). Thus, an accurate thermodynamic prediction of acid dew points does not appear possible (ref. 5). However, an equation based upon empirical data has been developed to predict the acid dew point (ref. 5):

$$\begin{aligned}(1/TDP) = {} & 0.002276 - 0.00002943 \ln P_{H_2O} \\ & - 0.0000858 \ln P_{H_2SO_4} \\ & + 0.0000062 (\ln P_{H_2SO_4})(\ln P_{H_2O})\end{aligned}$$

where TDP is the dew point in ^oK, and P_{H_2O} and $P_{H_2SO_4}$ are the partial pressures of H_2O and H_2SO_4, respectively, in millimeters of mercury.

In this study, this equation was used to determine the sulfuric acid dew points. The fraction of the sulfuric acid equilibrium concentration was parametrically assumed in the calculation of dew point. Two cases which bracket values quoted in the literature (ref. 2) were examined, one, assuming 10 percent of the sulfuric acid equilibrium concentration and the second assuming 1 percent. The equilibrium concentrations of H_2SO_4 and H_2O were calculated using the NASA chemical equilibrium computer program (ref. 6). To calculate the combustion product composition, a hydrogen-to-carbon ratio of a typical liquid fuel was input to the program, while the amount of sulfur in the fuel was varied parametrically.

A summary of the combined cycle assumptions used in this analysis is shown in Table 2. Gas turbine efficiencies were calculated in a previous study which investigated the combined cycle performance improvement when using a TBC (ref. 1). As in the previous study, the same steam cycle throttle conditions were used for all cases (8.375 MPA/510^o C (1200 psig/950^o F)). For the sulfur-free fuel cases in this study the feedwater inlet temperature to

the heat recovery steam generator (HRSG) is 106° C (222° F)(also as in the previous study). The feedwater heater arrangements used for the various cases are shown in figures 1 through 4. The arrangement shown in figure 1 applies to all of the sulfur-free fuel fired air-cooled cases, and to the water-cooled base case burning a sulfur-free fuel and not using TBC. To recover as much heat from the gas turbine exhaust as possible in these cases, deaerating of the feedwater is done as shown. However, for the air-cooled cases using the 0.8 percent sulfur fuel, the steam cycle feedwater heater train is arranged so that the water-inlet to the HRSG is raised to 28° C (50° F) above the surfuric acid dew point to avoid acid condensation on the relatively cold water tubes. The feedwater arrangement for these cases is shown in figure 2. One or two regenerative feedwater heaters are used to raise the HRSG feedwater to the appropriate temperature. Part of the water at the exit of the regenerative feedwater heaters is used to generate steam for the deaerating heater. Although, using this arrangement results in higher steam cycle efficiencies than the arrangement in figure 1, less heat can be recovered from the gas turbine. For the water-cooled case burning the sulfur-free fuel and using TBC the feedwater heater arrangement shown in figure 3 is used. In this case, the exhaust gas temperature from the gas turbine is sufficiently high, such that all of the exhaust heat from the gas turbine can be recovered down to the minimum stack temperature without the need to recover heat for deaerating. Extraction steam from the steam turbine is used for deaerating. The use of extraction steam in this way results in a more efficient steam cycle. Since all of the steam cycles in reference 1 used the feedwater arrangement as shown in figure 1, the feedwater arrangement shown in figure 3 results in a higher combined cycle efficiency for the water-cooled combined cycle using TBC than was reported in reference 1. This will be shown later. For the water-cooled cases using the 0.8 percent sulfur fuel, the feedwater arrangement shown in figure 4 is used. Here, as for the air-cooled cases, regenerative feedwater heating is used to raise the water inlet temperature to the HRSG to 28° C (50° F) above the dew point.

It is assumed that the minimum temperature difference (ΔT) between the gas turbine exhaust gas and the steam side in the HRSG is 28° C (50° F). This ΔT occurs at the economizer exit-boiler inlet, which is commonly referred to as the "pinch-point." For maximum heat recovery of the gas turbine exhaust, the stack temperature should be as low as possible. This would mean a stack temperature 28° C (50° F) above the HRSG water inlet temperature. Thus, for the sulfur-free fuel cases, the stack temperature would be equal to the HRSG water inlet temperature (106° C (222° F)) plus 28° C (50° F), or 134° C (272° F). Likewise, for the 0.8 percent sulfur fuel cases, the stack temperature would be 28° C (50° F) above the water inlet temperature, and since this feedwater inlet temperature is constrained to be 28° C (50° F) above the dew point, the stack inlet temperatures must be at least 56° C (100° F) above the dew point. Thus, for a fuel containing sulfur with a dew point of 121° C (250° F), the minimum stack temperature, using these groundrules, would be 177° C (350° F). The loss in heat recovery between 134° C (272° F) to 177° C (350° F) would cause a decrease in the combined cycle efficiency. (In the previous study (ref. 1) the stack temperature was kept constant at 149° C (300° F) for all cases so as to evaluate the effects of TBC separately from design considerations such as stack temperature.)

The TBC which has been mentioned in this investigation consists of a yttria-stabilized zirconia thermal barrier (0.038 cm (0.015 in.) thick) with a NiCrAlY bond coat (0.010 cm (0.004 in.) thick). The thermal conductivities of these materials are as shown in Table 2.

Auxiliary power requirements were not included in the performance results. Auxiliary power requirements for liquid fuel fired combined cycles are typically small compared to the total power produced.

RESULTS

The results of the dew point calculations are shown in figure 5 for various air-to-fuel ratios and fuel sulfur contents. For a particular sulfur content, the dew point decreases with increasing air-to-fuel ratio because the partial pressure of H_2O and H_2SO_4 decreases. As can be seen, there is about a 22° C (40° F) difference in the dew point estimate between the 10 percent and 1 percent of H_2SO_4 equilibrium concentration assumptions. Also note that the difference in dew point between the 0.2 percent and 0.8 percent sulfur content curves is about the same in both cases.

In Table 3, the combined cycle performance results are shown for both air-cooled and water-cooled gas turbines. For the air-cooled gas turbines, the first two cases represent the base case at a turbine inlet temperature of 1205° C (2200° F) without the use of TBC and using the sulfur-free fuel. The first case, taken from reference 1, has a stack temperature of 149° C (300° F) and an efficiency of 0.458. The second case has the 134° C (272° F) stack temperature (28° C (50° F) + HRSG inlet water temperature) used in this study, resulting in a combined cycle efficiency of 0.464. The increase in combined cycle performance is due to the increased heat recovery of the gas turbine exhaust in the latter case. The next two cases show the increased combined cycle performance attributable to the use of TBC with both the 149° C (300° F) and 134° C (272° F) stack temperatures. The increase in efficiency is 1.4 percentage points for the 134° C (272° F) stack temperature cases. The last two cases listed in Table 3(a) indicate the combined cycle efficiency using the 0.8 percent sulfur fuel and constraining the stack temperature as indicated to avoid H_2SO_4 condensation. The results are shown for both assumptions of sulfuric acid conversion as previously mentioned. For the 10 percent assumption, the efficiency using the 0.8 percent sulfur fuel is 0.8 percentage points lower than when using a sulfur-free fuel. For the 1 percent assumption, the difference is 0.4 percentage points. Thus, when using a sulfur-free fuel, a gain of 1.4 percentage points in efficiency could be achieved with the use of TBC. If, in addition to using a TBC, a cheaper, high sulfur fuel is used, a gain of 0.6 to 1.0 percentage points in efficiency could still be achieved.

The results for the water-cooled system cases are shown in part (b) of the table. Again the first two cases indicate the combined cycle system performance for the base case without TBC burning the sulfur-free fuel as reported in reference 1 (149° C (300° F) stack temperature) and as recalculated with a stack temperature of 134° C (272° F). In the third case, the combined cycle system performance with TBC has been modified from that reported in reference 1 to account for a more efficient steam cycle arrangement, as has been previously mentioned. This consisted of using extraction steam from the steam turbine for deaerating (fig. 3) instead of recovering heat from the gas turbine exhaust for this

purpose (fig. 1), as was done in reference 1. The increase in combined cycle performance is from 0.487 (as reported in ref. 1) to 0.495. The efficiency with a 134° C (272° F) stack temperature is 0.497. The increase in performance due to the use of TBC for the 134° C (272° F) stack temperature is 2.3 percentage points, while in reference 1, it was 1.5 percentage points using the less efficient steam cycle.

In the last two cases listed in Table 3(b), the efficiencies using the 0.8 percent sulfur fuel are shown. For the 10 percent of equilibrium H_2SO_4 concentration assumption, the combined cycle efficiency is 0.7 percentage points lower than the sulfur-free fuel case and for the 1 percent assumption it is 0.5 percentage points lower. The gain in efficiency due to the use of TBC is 2.3 points using a sulfur-free fuel. The gain using a TBC and switching to a cheaper, high sulfur fuel over the base case without TBC is 1.6 to 1.8 percentage points.

CONCLUDING REMARKS

It has been shown that the maximum effect on combined cycle efficiency of using fuels containing sulfur is a decrease of less than 1 percentage point when the fuel sulfur content is constrained by environmental restrictions. Likewise, the use of thermal barrier coatings (TBC) is shown to potentially increase the combined cycle efficiency by 0.6 to 1.0 percentage points with air-cooled gas turbines and 1.6 to 1.8 percentage points with water-cooled gas turbines when burning fuel oils containing sulfur. Thus, the use of thermal barrier coatings, which may permit the use of the less expensive, minimally-processed fuels, would result in increased efficiency.

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TABLE 1. - SUMMARY OF COMBINED CYCLE CASES INVESTIGATED

(a) Air-cooled gas turbines.

Turbine inlet temp., °C (°F)	Fuel sulfur content, %	With (W) or without (W/O) TBC
1205 (2200)	0	W/O
1370 (2500)	0	W
1370 (2500)	0.8	W

(b) Water-cooled gas turbines.

Turbine inlet temp., °C (°F)	Fuel Sulfur content, %	With (W) or without (W/O) TBC
1649 (3000)	0	W/O
1649 (3000)	0	W
1649 (3000)	0.8	W

TABLE 2. - SUMMARY OF ASSUMPTIONS

GAS TURBINE:	
Compressor Pressure Ratio:	
Turbine inlet temp. = 1205° C, 1371° C (2200° F, 2500° F)	12
Turbine inlet temp. = 1649° C (3000° F)	16
Compressor polytropic efficiency	0.9
Turbine polytropic efficiency	0.9
Combustor pattern factor	0.2
STEAM CYCLE:	
Throttle conditions, MPa/°C (psig/°F)	8.375/510 (1200/950)
Turbine adiabatic efficiency	0.8
Condenser pressure, Mpa (in Hg)	0.0084 (2.5)
Minimum HRSG ΔT, °C (°F)	28 (50)
Water temp. into HRSG, °C (°F)	
Fuel without sulfur	106 (222)
Fuel with sulfur	Dew point + 28° C (50° F)
STACK TEMPERATURE, °C (°F)	Water temp. into HRSG + 28° C (50° F)
GENERATOR EFFICIENCY	0.987
MAXIMUM GAS TURBINE BLADING SURFACE METAL TEMPERATURE, °C (°F)	
Air Cooling	815 (1500)
Water Cooling	538 (1000)
THERMAL BARRIER COATING PARAMETERS	
Zirconia Conductivity, MJ/sec-m^2-°C (Btu/hr-ft^2-°F)	4.3×10^{-6} (0.75)
NiCrAlY Conductivity, MJ/sec-m^2-°C (Btu/hr-ft^2-°F)	
Air Cooling	2.2×10^{-5} (3.9)
Water Cooling	1.9×10^{-5} (3.4)
Zirconia Thickness: cm (in.)	0.038 (0.015)
NiCrAlY Thickness: cm (in.)	0.010 (0.004)

TABLE 3. - EFFECT ON COMBINED CYCLE EFFICIENCY OF USING TBC WITH HIGH SULFUR RESIDUAL OIL

(a) Air-cooled turbines.

Turbine inlet temp., °C (°F)	Fuel	With (W) or without (W/O) TBC	% of equil. H_2SO_4 concentration	H_2SO_4 solution dew point, °C (°F)	Water temp. into HRSG, °C (°F)	Stack temp., °C (°F)	Combined cycle efficiency
1205 (2200)	No S	W/O	---	---------	106 (222)	149* (300*)	0.458*
1205 (2200)	No S	W/O	---	---------	106 (222)	134 (272)	0.464
1370 (2500)	No S	W	---	---------	106 (222)	149* (300*)	0.475*
1370 (2500)	No S	W	---	---------	106 (222)	134 (272)	0.478
1370 (2500)	0.8% S	W	10	137 (278)	165 (328)	193 (378)	0.470
1370 (2500)	0.8% S	W	1	113 (235)	141 (285)	169 (335)	0.474

(b) Water-cooled turbines.

Turbine inlet temp., °C (°F)	Fuel	With (W) or without (W/O) TBC	% of equil. H_2SO_4 concentration	H_2SO_4 solution dew point, °C (°F)	Water temp. into HRSG, °C (°F)	Stack temp., °C (°F)	Combined cycle efficiency
1649 (3000)	No S	W/O	---	---------	106 (222)	149* (300*)	0.472*
1649 (3000)	No S	W/O	---	---------	106 (222)	134 (272)	0.474
1649 (3000)	No S	W	---	---------	106 (222)	149* (300*)	0.495**
1649 (3000)	No S	W	---	---------	106 (222)	134 (272)	0.497
1649 (3000)	0.8% S	W	10	143 (288)	170 (338)	198 (388)	0.490
1649 (3000)	0.8% S	W	1	119 (245)	146 (295)	174 (345)	0.492

*Results found in reference 1.
**Results modified from reference 1 to account for a more efficient steam cycle configuration (ref. 1 efficiency = 0.487).

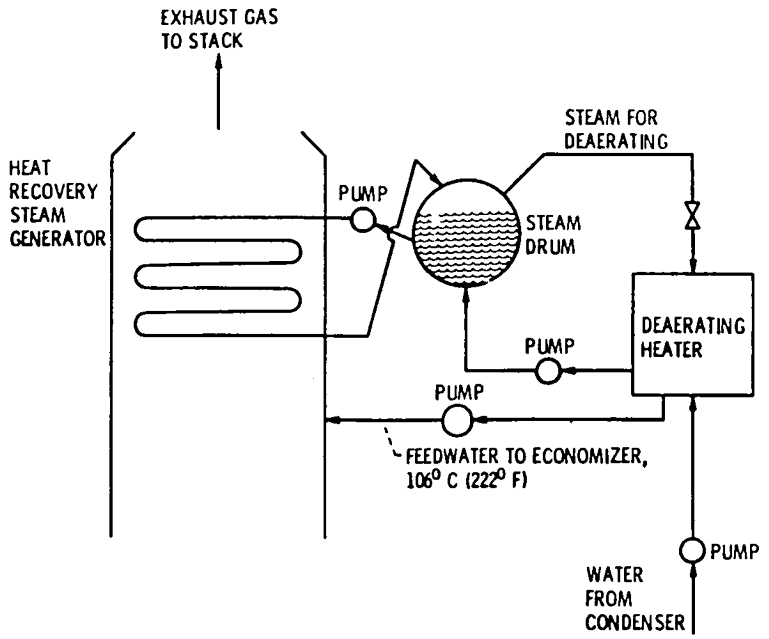


Figure 1. - Deaerating heater arrangement for clean fuel fired cases, air-cooled and water-cooled w/o TBC.

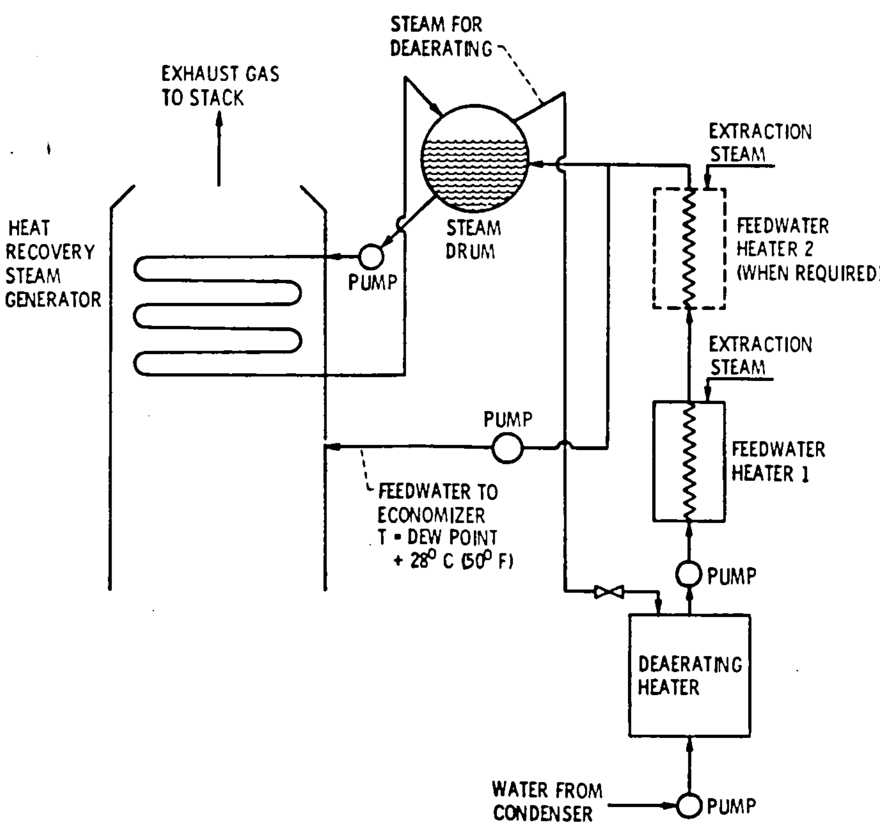


Figure 2. - Feedwater heater arrangement for air-cooled cases burning sulfur-fuel and requiring high HRSG inlet water temperatures.

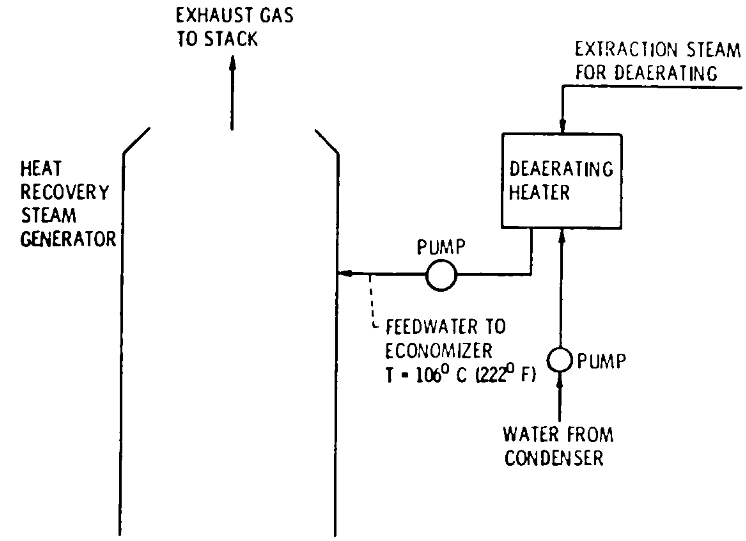


Figure 3. - Deaerating heater arrangement for water-cooled gas turbine/combined cycle using TBC and sulfur-free fuel.

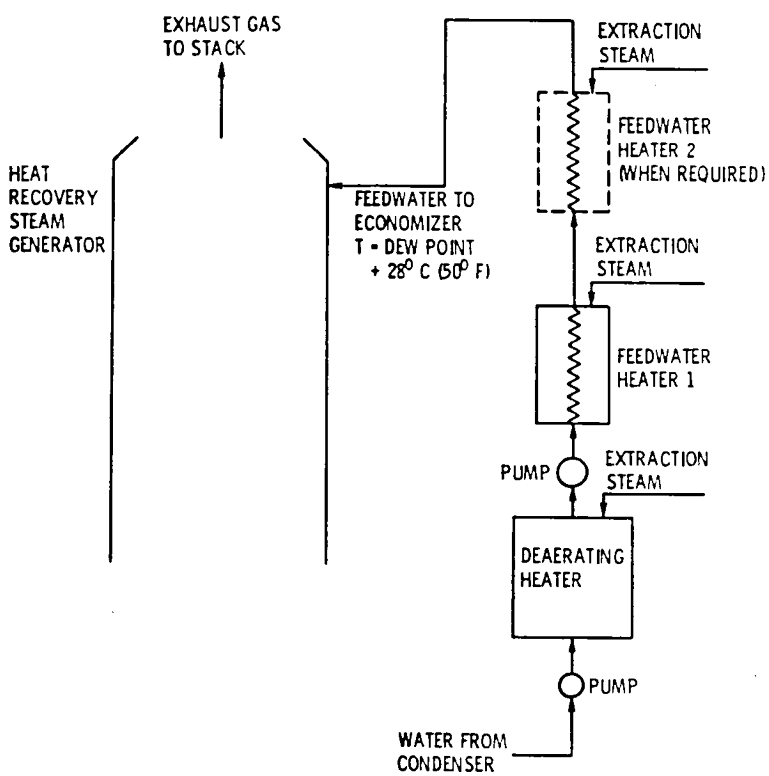
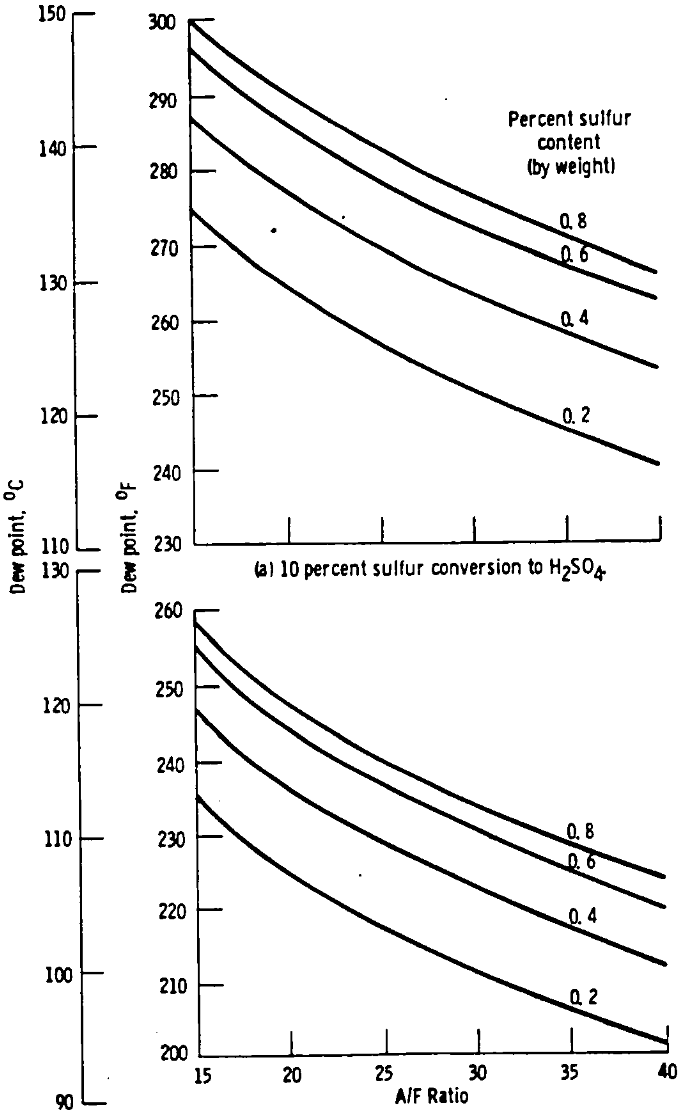


Figure 4. - Feedwater heater arrangement for water-cooled gas turbine/combined cycle using TBC and high sulfur fuel.



(a) 10 percent sulfur conversion to H_2SO_4.

(b) 1 percent sulfur conversion to H_2SO_4.

Figure 5. - H_2SO_4 Solution dew point as a function of air/fuel ratio and fuel sulfur content.

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16. Abstract

To avoid condensation of sulfuric acid in the gas turbine exhaust when burning fuel oils containing sulfur, the exhaust stack temperature and cold-end heat exchanger surfaces must be kept above the condensation temperature. Raising the exhaust stack temperature, however, results in lower combined cycle-efficiency compared to that achievable by a combined cycle-burning a sulfur-free fuel. The maximum difference in efficiency between the use of sulfur-free and fuels containing 0.8 percent sulfur is found to be less than one percentage point. The effect of using a ceramic thermal barrier coating (TBC) and a fuel containing sulfur is also evaluated. The combined-cycle efficiency gain using a TBC with a fuel containing sulfur compared to a sulfur-free fuel without TBC is 0.6 to 1.0 percentage points with air-cooled gas turbines and 1.6 to 1.8 percentage points with water-cooled gas turbines.

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